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NOTES ON THE PROBLEM OF THE ORIGIN OF THE LUNAR CRATERS

By W. W. Campbell

In recent years I have been deeply interested in the so-called Meteor Crater in Central Arizona. This crater, situated about twenty miles west of Winslow, and six miles south of the main line of the Santa Fe Railway, is four-fifths of a mile in diameter at the rim, its present depth is approximately 500 feet, and it has a general form resembling in all respects that of the lunar craters which are comparable in size to it. The Arizona crater is familiar to geologists; several geologists have visited the crater and have made extensive studies of it. The literature of the subject, embracing full two scores of papers, is due almost wholly to those whose chief interests are geologic. Their conclusions as to the origin of the crater are widely different. Gilbert, who was the first to study the subject thoroly, and Darton, whose papers are amongst the most recent, favor the hypothesis of an internal-explosion origin. Other geologists, notably Fairchild and Merrill, favor strongly the idea of origin by meteoric impact. Barringer, of Philadelphia, whose commercial company acquired legal title to the region containing the crater, and who made large expenditures of time and money in drilling in the crater bottom for meteoric iron and other valuable metals, holds firmly to the meteoric hypothesis. Astronomers have not, in my opinion, given the crater the attention which it deserves from them. To the best of my knowledge no astronomer has visited the crater, and its existence and character have not been recognized in astronomical text books. It is hoped that this neglect may soon be remedied.

My interest in the mooted question of the origin of the meteor crater renewed the interest which I felt in the origin of the lunar craters in the 1890's, when engaged in showing the Moon thru the 36-inch refractor to many thousands of Saturday evening visitors. At that time it did not occur to me that the volcanic origin of the lunar craters was in serious doubt, and I did not think of reviewing the subject in print. Since then, several published articles have seriously questioned this explanation of the crater origins. Knowing that I have in the past year been considering the probable origin of the lunar craters, in search for assistance in solving the problem of the origin of the Arizona crater, the editors of these PUBLICATIONS requested me to contribute an article on this subject to the present lunar number of this journal. It is not my purpose to attempt an exhaustive study of the lunar craters, but merely to call attention, under the heading of "Notes," to some of the less familiar, but possibly more important, pieces of evidence as to their origin.

Two hypotheses as to the origin of the lunar craters are well-known:

1. They are a result of volcanic activity on the Moon—just as terrestrial volcanoes are one of the results of volcanic activity on the Earth.
2. They are a result of collisions of rapidly-travelling meteoric bodies with the Moon.

The first hypothesis is more than two centuries old, and is favored by the great majority of astronomers who have given thought to the subject. The second hypothesis appears to date from Proctor, in 1873; it is preferred by a few astronomers, apparently by a larger proportion of geologists, and by many others interested in the physical sciences. References to one or both of the hypotheses are numerous in the astronomical literature of the last half century, but philosophic treatments of the problem, presenting the pros and cons of both hypotheses, without prejudices as to the final results, are scarce. In *Popular Astronomy*, **18**, 137-144, 1910, See has marshalled the leading arguments in favor of the meteoric hypothesis. In *Proceedings American Academy Arts and Sciences*, **47**, 730-733, 1912, Elihu Thomson makes a strong case for the same hypothesis.

It seems to me a mistake to argue for either origin exclusively. May not both sources have their representative craters? Existing telescopes do not let us examine the smaller craters in such detail as to enable us to assign their origins to their true causes. To be visible at all, a crater must apparently have a diameter of the order of a quarter of a mile and the illumination by the Sun must be just right, and for craters even one or two miles in diameter the details of structure are thus far almost as a sealed book.

Millions of meteors collide with the Earth's atmosphere every twenty-four hours, but very few of these get thru to the Earth's surface. Only one known terrestrial crater, the small one in

Arizona, seems to admit the possibility of a meteoric origin. The Moon, on the contrary, is practically without atmosphere, and hundreds of thousands of meteors probably collide with its surface every terrestrial day. The scarcity of great meteoric craters on the Earth is not to be explained by the resistance of the atmosphere to meteoric bombardment: meteors massive enough and speedy enough to create great craters on the Moon would pay no appreciable attention to the Earth's atmosphere. They would come thru the atmosphere, to the rock or water surface of the Earth, with speed and mass not appreciably reduced. If the lunar craters are really of meteoric origin, then the Earth must likewise have possessed in profusion meteor craters of great size. As we have said, not one such large crater is known to exist today. If they existed in past ages, they must have been obliterated by erosion, sedimentation, flows of molten rocks, or other results of meteorologic and geologic forces. The Moon, free from appreciable water and air, would doubtless give its craters much longer life.

We shall consider only the larger craters of the Moon. Their visible details afford a basis for testing hypotheses and drawing conclusions.

There appear to be no reasons for questioning that many truly geologic forces have been prominent in shaping the Moon's destiny. The lunar mountain ranges are in many respects comparable with terrestrial ranges. There are geologic faults, as on the Earth, and perhaps on a larger scale than with us; for example, one of the most conspicuous features of the Moon is an apparent geologic fault sixty miles long, approximately 1,000 feet high, situated about fifty miles easterly from the crater Thebit; it is known as the Great Wall. Many of the *maria* or lunar "seas," are in my opinion overflowed areas,[1]—just as immense terrestrial areas were overflowed by molten lava. The *maria* contain the remnants of many craters in which only the summits of the crater rims continue unsubmerged. Indeed, there are many cases in which only the high points of crater rims project above the submerging materials.

In the *maria* there are cases of apparent radial flows from craters which cease suddenly, apparently due to the flooding of the lower surrounding country by molten, flowing materials. Cassini and, less striking, Archimedes are examples. Aristillus, on the contrary, is surrounded by long radiating streamers whose outer ends have not been overflowed, thus suggesting that in this crater we see the results of the latest activity in this region. In Mare Humorum, admirably pictured by the Paris charts, plate XL, a lava flow has submerged those sections of the rims of the craters Lee, Doppelmayer, Gassendi, and Hippatus, which face the *mare*. The "flow marks" on the *mare* surface seem to be visible—as if the origin of flow had been more or less central in the *mare*. The eastern edge of Mare Crisium affords good examples of submerged craters, and likewise of flow marks. Near the south end of Mare Nectaris a flow has apparently submerged the north wall of the crater Fracastor, or possibly has melted the wall down. There are numerous cases of craters almost wholly submerged in the Ocean des Tempêtes, Paris chart LXII, and in the Mer des Nuages, Paris charts XIV and XIX. An excellent example is the extreme top of a large crater rim showing thru the submerging stratum at a point about two-fifths of the way from Eratosthenes to Archimedes.[2] The remains of submerged craters are especially numerous in Mare Nubium; the crater Kies is a prominent example—Paris chart VIII. Scores of similar cases can be found by examining the numerous lunar *maria* when the illumination of each is just right.

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[1] Professor E. W. Brown has called my attention to Franz's map of Average Levels of the lunar surface, in Koenigsberg *Beobachtungen*, **38**, 1899. This map shows that the southwest half of the visible hemisphere of the Moon, which is rich in craters and poor in seas, is more elevated than the northeast half, which is poor in craters and rich in seas. This is in harmony with the ideas that the southwest half in general has been elevated by the volcanic activities which accompany crater formation and that the northeast half should be the scene of greatest lava overflows.

The number of active volcanoes on the Earth in the last hundred thousand years was probably in excess of a thousand. The number positively known to have been active in historical times exceeds three hundred. Inasmuch as the levelling influences on the Moon are comparatively feeble and inactive, and the existence of mountains, geologic faults, and geologic flows can scarcely be doubted, is there cause for surprise that the number of lunar craters, if due to volcanic causes, operating thru many millions of years, should be numbered in the thousands?

If the impacts of great meteors with the lunar surface have been as numerous as the number of existent craters, should we not expect abundant evidences of impacts at all angles of incidence, varying from the tangential to the vertical? To the best of my knowledge and judgment there is only one feature of the lunar surface which suggests an impact differing appreciably from strikes in directions making small angles with the perpendiculars to the surface. In the Valley of the Alps we seem to have a collision effect, due to a massive meteoric body, possibly a mile or two in diameter, which all but missed the Moon, and therefore struck the lunar body in a direction nearly coincident with that of a tangent to the surface. The lunar Alps, about ninety miles wide at the point concerned, are ploughed nearly thru and down to "sea level," so to speak. The resulting Valley of the Alps, following Webb's description, is a great cut in a straight line thru the very loftiest part of the range, 83 miles long, 3½ to 5¾ miles broad, with precipitous sides and a depth of at least 11,500 feet. The bottom of the Valley is described as flat, but it is said that Klein saw what he called the results of landslides from the edges of the Valley. It is as if a great meteorite, travelling northerly over Italy, had struck the southern flank of the Alps at Como and ploughed its way horizontally thru the Alps as far as Lucerne. It is as if a great meteorite had ploughed its way thru the Sierra Nevada range in California, from the foothills east of Fresno easterly thru the Mount Whitney region to the floor of the valley on which the village of Lone Pine is situated. There may be a lingering doubt as to whether a great metallic meteorite travelling with a relative speed of forty miles, more or less, per second could save itself from volatilization or other destructive consequences while penetrating and overcoming the resistance of a great mountain range on a course of 83 miles. There would probably also be a tendency, during the several seconds occupied in the operation, for the projectile to strike a glancing blow or to break into fragments. It is possible that the mathematicians could deduce suggestive alternatives as to the consequences of an impact of the character and magnitude described.

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[2] See Plate IV of this number.—Editor's note.

There appear to be no lunar features clearly illustrating the effects of collisions by massive meteoric bodies whose angles of incidence lie between that assumed to have attended the formation of the Valley of the Alps and those postulated as the sources of the lunar craters. This is a fact in strong opposition to the impact theory of crater origin.

A great many laboratory experiments have been made by throwing or firing projectiles of various kinds and sizes upon resisting surfaces of different character, in order to study the forms of the resulting craterlets. These experiments have led to interesting results, but I do not believe there is any chance that they afford serious evidence as to the origin of any lunar craters large enough to be seen with telescopes, say one thousand feet in diameter and greater. A laboratory crater, whose diameter is only a few inches or a foot or two, must not be expected to tell us much about the origin of a crater 250,000 feet (50 miles) in diameter. A laboratory crater may have a central peak an inch or two or three inches high; will that tell us anything of value as to the origin of central peaks 6,000 feet high in lunar craters? By far the most interesting laboratory experiments of this nature conducted to date were those described by Ives in the *Astrophysical Journal* for November, 1919, in which the origins were the explosions of powerful bombs dropped upon the Earth's surface from airplanes. The largest craters developed by this means were of the order of one hundred feet in diameter, and possibly thirty feet in depth. Would we be justified in reasoning from these craters to the lunar craters, whose diameters are forty, fifty, and sixty miles, and whose depths are four, five, and six thousand feet? I think such comparisons must be of very limited value.

Advocates of the meteoric hypothesis of lunar origins have laid great stress upon the fact that many of the craters have central peaks three thousand, five thousand, or as much as seven thousand feet high. These central peaks are ascribed to reactions from the impacts, such as are illustrated by the central peaks in some of the small laboratory craters. While the number of these characteristic lunar peaks is very considerable, they are by no means the rule. The vast majority of lunar craters contain no central peaks. William H. Pickering is authority for the statement, further, that central peaks rarely occur in craters less than four miles in diameter. Do the central peaks in the little laboratory craters then mean anything in the lunar problem? If these central peaks on the Moon are reactionary results of impacts, why should they be so relatively few? Why should they not be the rule instead of the exception? If one general effect of impact is the throwing up of crater walls which have the common characteristics of steep interior slope and more gradual outer slope, why should they not have the common effect of central peaks? Another fact is, the existing peaks in many craters are not central. Further, in a considerable number of craters, there is not a single central peak, but two or more peaks near the center.

Let us imagine that a great meteor did actually produce by impact a lunar crater fifty miles in diameter, with a central peak five or six thousand feet high. What improbabilities does this assumption encounter? The crater wall and central peak, on this assumption, were created by one cataclysm, in a few seconds at the most. The materials left in the interior of the crater could scarcely avoid being reduced to liquid form. In any case the enclosing ring, a very steep mountain wall, so to speak, was thrown up suddenly and it stayed there. A central peak was thrown up suddenly and, notwithstanding its probable liquidity or viscosity, remained standing in opposition to the force of gravity. Are not these results highly improbable and essentially unthinkable? If, for any reason, the formation of the circular crater wall demands a long-continued molten state of the interior, what does the simultaneous formation of the central peak demand in this regard? We know that in many of the large craters, Tycho for example, the interior wall of the rim is beautifully terraced; why are not the central peaks similarly terraced?

While showing visitors thru the 36-inch refractor twenty-five and more years ago I was able to observe that some of the central peaks of lunar craters had light and shade effects on their extreme summits due to the existence of central summit craterlets, such as are known to exist in the summits of many terrestrial volcanic peaks. I made no notes on the subject, as I supposed these features were well known to students of the Moon. Last summer I recalled these observations and, realizing the critical bearing of such summit craterlets upon the theory of the origin of the central crater peaks and therefore upon the origin of the craters themselves, I searched the literature of the Moon carefully for published references to the subject. Gore says that "M. Gaudibert observed some high volcanic cones on the Moon with small crater openings on the top." These observations refer not to central crater cones, but to random peaks unconnected with craters. In William H. Pickering's *Lunar and Hawaiian Features Compared*, page 156, we read, "Between (the craters) Kies and Mercator is seen a comparatively small cone with a minute crater on its summit. It proves to be nine miles in diameter at the base, and two thousand feet in height, while the crater itself measures half a mile in diameter." This likewise refers to an outside or ordinary mountain peak. In November, 1919, I inquired of Professor Pickering whether his note books contained records of small craters at or very near the summits of the peaks which are central or nearly so in many large lunar craters. He responded that he had casually noticed a few such craterlets, for example at the summits of the central peaks in the craters Albategnius, Plinius, Capella, and Kant. He stated further that "outside of the craters there are many examples of high peaks which carry minute summit craters and are thus analogous to terrestrial volcanoes." His letter referred to eight such volcanic peaks located between Copernicus and Kepler. Shortly following the receipt of my inquiry Professor Pickering had a perfect night and he examined several of the lunar craters which had central peaks, with the result that he found summit craterlets in the central peaks of Timocharis, Herschel, Alpetragius and Pitatus.[3] He further made the important comments: "Since in most cases recorded these summit craterlets are less than a mile in diameter, running down to a size such that we can only just be certain of them, it is clear that there must be numerous others just beyond our range of vision." At about the same time Dr. Aitken and I examined the Moon on two evenings with the 36-inch refractor, and we had no difficulty in seeing several central-peak craterlets, of whose existence we had no prior knowledge. These craterlets seem to be most readily seen from eighteen to thirty-six hours after the Sun has risen on them or before the Sun will set on them. I am under great obligations to Professor Pickering for the valued information quoted above and for the privilege of using it.

Must we not agree that the unquestioned existence of craterlets in the summits of central crater peaks is absolutely fatal to the impact theory of the origin of those peaks, and at the same time in full and complete harmony with the hypothesis of the volcanic upbuilding of those peaks? It is known to all students of volcanism that central peaks in terrestrial volcanic structures are fairly numerous and that a very large proportion of them still retain undoubted evidence of summit craterlets, some of these craterlets in essentially perfect states of preservation.

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[3] See Table I of Professor Pickering's article for further details.—Editor's note.

One of the strongest arguments for the impact theory of crater origins on the Moon is based upon the fact that the floors of the craters are not only surprisingly far below the level of the tops of the crater rims, but are frequently several thousand feet below the level of the surrounding plains: the tremendous impacts of meteorites are credited with having excavated the resulting crater interiors to the great depths observed, the materials having been thrown out upon the adjacent areas. Could such a cataclysmic action, say one capable of excavating a crater fifty miles in diameter and five thousand feet deep in a second or two, or in a very few seconds at the most, avoid liquifying the crater interior? If a central peak were thrown up as a reaction effect, would it not be of viscous consistency and be pulled down immediately by lunar gravitation?[4] Could the interior wall of the rim remain so steep as we observe it? Could the interior walls of crater rims be terraced so markedly as we observe this effect in scores of craters, for example, Arzachel, Tycho, Copernicus, etc., if the impacts had emptied the crater bottoms down to their present low levels?

To me a vastly more probable description of the origin of a lunar crater and its central peak is the well-known one held by those who look with favor upon the hypothesis of volcanic origins. Whatever the beginnings of a volcanic lunar crater may have been there comes a time, probably early in its history, when the interior fills with molten materials which well up thru the central duct or neck that leads down to a considerable depth in the lunar body. This molten material overflows the rim of the crater, building up the rim, increasing the outer diameter of the rim structure, and some of the molten materials flow out upon the surrounding areas. The exterior walls of the rim cool and solidify, whereas the interior walls liquify from contact with the sea of molten matter, and the interior diameter of the crater ring increases. These processes probably continue intermittently thru long ages of lunar evolution. The molten sea of matter lowers in level thru the withdrawing of the materials into the Moon's interior; this is a process observed frequently in active terrestrial craters. The filling of the crater bowl probably occurs a great many times, with consequent overflowing and upbuilding of the rim and the increasing of its diameter by the melting down of its interior wall. Toward the end of the major stage of volcanic activity the successive fillings of the crater bowl probably are less and less complete, leading in many cases to the formation of terraces on the inner wall of the rim. When activity ceases the floor of the crater is left comparatively level. In many craters the volcanic activity is again renewed, but on a minor scale, with the effect that central peaks are built up by the escape of volcanic materials from the summit craterlets which terminate the central ducts or necks leading down into the body of the Moon. These processes could well and probably did consume many millions of years.

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[4] In the laboratory craters which had central peaks there was no liquefied or viscous condition and no appreciable gravitational component, to erase the diminutive central peaks.

A study of the so-called lunar rills leads unavoidably, I believe, to the conclusion that they are not the results of very oblique meteoric impacts, as some observers have suggested, but that they represent ordinary geologic processes. Many of the rills have craters situated upon them, in some cases at what may be called strategic points. The crater Hyginus is located precisely at a sharp angle in one of the most conspicuous of lunar rills—see Paris chart XLVI. There are other craters of fair size on the strongly curved rill east of the crater Bouillaud—Paris charts XLIX and VIII. The forms of both the rills referred to seem quite impossible on the basis of meteoric origin. The craters upon them suggest that the rills are the outward evidences of lines of weakness in the lunar surface strata.

The bright streamers which radiate from the craters Kepler, Olbers, Tycho, Copernicus, etc., are exceedingly interesting objects, and their presence must be accounted for by any successful hypothesis of crater origins. We may dismiss at once the idea that these brighter streaks are the results of the filling up of cracks radiating from the craters by materials of lighter color from the interior of the Moon. The streamers from several craters are remarkably straight (*i. e.*, arcs of great circles on the lunar surface) and in many cases these streamers run indifferently over level plains, crater bottoms, crater walls, and mountain structure. They are difficult to explain on other assumptions than that they are meteoric splashes or volcanic projectile discharges from craters. Some of these streamers, notably several extending out from Tycho, are many hundreds of miles in length. It is not very difficult to imagine that the brighter materials responsible for the streamers could have left their crater origins, as projectiles, with speeds sufficient to carry them over a large surrounding area of the Moon, where they are now observed. We need only to remember that the force of gravity at the lunar surface has but one-sixth its value at the Earth's surface, and that the motions of particles projected from the craters would meet with no atmospheric resistance, certainly with no appreciable resistance. Dust particles of low density would travel as far as massive pieces of high density. Comparatively low velocities of ejection from the craters would carry the ejected materials thru long distances, and the materials would be distributed on elemental lines, more or less long, which point toward the crater origins.[5] It is quite probable that a meteoric impact capable of producing the crater Tycho could eject fragments of matter from the crater with speeds sufficient to carry them to the extreme limits of the system of radiating streamers which have that crater for their focus. It is at least equally easy to imagine that a volcanic eruption in the crater Tycho could eject liquid or dust particles with speed sufficiently great to account for the distribution which we observe. Inasmuch as the walls, the terraces, and the central peak of Tycho are just what we should expect from a volcanic origin of the crater, need we struggle strongly against the volcanic eruption hypothesis of the remarkable system of streamers which center at that point? An examination of the immediate surroundings of Tycho shows that it has had little interference from activity in the neighborhood. Tycho is therefore the symbol of latest volcanic activity in the area which it occupies. This being true, we need not be surprised that the bright streamers radiating from Tycho are drawn across the more ancient topographic features upon which the projected Tychonic materials have fallen.

The streamers which radiate from Copernicus are not so straight as those from Tycho. Some of the streamer materials may have reached their present destination on ejection lines lying entirely above the surface of the Moon, whereas other materials may have followed the usual processes of volcanic flow. A critical examination of the Copernican region will show a few ancient craters, now almost totally submerged, across which the Copernican streamers have left their mark, whereas other craters in this region, apparently unaffected by the earlier submerging overflows, are untouched by the Copernican streamers under consideration. These perfect and complete craters are probably of more recent origin than Copernicus itself.

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[5] Professor E. W. Brown, when at Mount Hamilton recently, deduced from a hasty calculation that particles of matter ejected from a crater, such as Tycho, at a favorable angle with the lunar surface and a speed of the order of one and one-third miles per second, could be carried to points one thousand miles from the crater origin.

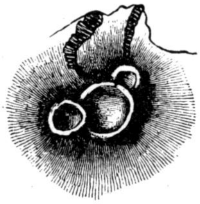

FIG. 1. Plan of the volcanic cone of the Island of Vulcanello (north of Sicily), showing three successive and overlapping craters.—From Geikie's Text Book of Geology, Vol. 1, p. 323.

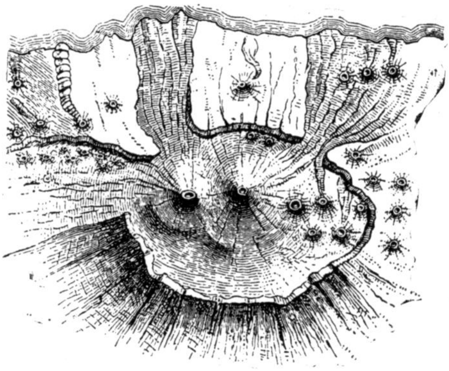

FIG. 2. Plan of the Peak of Teneriffe, showing the large crater and 32 minor craters.—From Geikie's Text Book of Geology, Vol. 1, p. 330.

It has been objected to the volcanic hypothesis of crater origin that overlapping lunar craters do not show the effects which volcanic flows inside of and over crater walls would lead us to expect. The first illustration in this paper, the plan of the volcanic cone on the island of Vulcanello, shows three successive and overlapping terrestrial craters with characteristics which should discount the objection.

It has been objected that the existence of great numbers of small craters on the floors of great craters and even upon the tops and inner and outer slopes of crater walls is opposed to the volcanic hypothesis and in favor of the meteoric. The second illustration in this paper, the plan of the Peak of Teneriffe, showing a large crater, as affected by meteorologic and other conditions, with as many as thirty-two minor craters superimposed upon the original crater, should remove the objection.

In concluding these notes on lunar characteristics, I am disposed to express my conviction that the principal surface features are the ordinary products to be expected from evolutionary processes purely geologic; that we may, on this hypothesis, assign to many surface features their relative ages; and that, while some small craters may possibly be the results of meteoric impact, the evidence for the volcanic origin of the larger craters is overwhelmingly strong.